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The ratio of deuterons to protons in photo-nuclear reactions determined by the method of grain-counting

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With 8 figures in the text

Summary

An investigation has been made into the usefulness of the grain-counting method for identification of short tracks. Efforts have been made to separate deuterons from protons by grain-counting in the last 40 μ of the track. The protons and deuterons were obtained by photo-disintegration of metals by bremsstrahlung of 30 MeV maximum energy. At the same time the photo-deuteron yield has been compared with the photo-proton yield from cobalt and copper. No marked difference in the ratio, $Y(\gamma, d)/Y(\gamma, p)$, was obtained. The ratio observed was 0.22 for cobalt and 0.16 for copper.

Introduction

A well-known method for mass determination of charged particles is grain-counting with range determination in tracks in nuclear emulsions (1). Long tracks are required in order to obtain a satisfactory resolution by separation of singly charged particles with different masses. Sometimes, however, the particles to be investigated possess a low initial energy. It would therefore be interesting to study how far in the range of low energies the method of grain-counting can also give information about the kind of particles to be found.

The aim of this work was to separate deuterons from protons by grain-counting in the last 40 μ of the tracks in E.1 Ilford emulsions. The protons and deuterons were obtained by photo-disintegration of metals, using bremsstrahlung of 30 MeV maximum energy from the University of Lund synchrotron.

At low and medium X-ray energies the statistical model (2), corrected for the direct photo-nuclear effect (3, 4), can satisfactorily give an account of the photo-emission of protons and neutrons. The model fails, however, to explain the high yield of photo-deuterons that is experimentally known over a long period (5–8). The yield of photo-deuterons, according to the statistical model, ought to be several ten-powers less than that experimentally shown. It is suggested that this extreme photo-deuteron effect depends on some sort of pick-up process (9), where the outgoing neutron or proton picks up a nucleon of opposite kind and leaves the nucleus as a deuteron.

The effect has been thoroughly investigated at high X-ray energies, 300 MeV, (10–12). The ratio of the photo-deuteron to the photo-proton yield, $Y(\gamma, d)/Y(\gamma, p)$, seems to vary continuously with the mass number from 0.12–0.24. At medium and low energies, however, quite strong fluctuations of the deuteron yield from element to element have been observed (5, 6, 8, 13, 14), This should indicate that the deuteron emission is dependent on the nuclear structure.

The aim of this work was not only to investigate the method of grain-counting in short tracks, but also to study the strong fluctuation of the photo-deuteron yield from the adjacent elements, cobalt and copper, reported by the Pennsylvania group (5, 14).

Experimental Procedure

Exposure

The experimental arrangement for the registration of the photo-protons and deuterons is shown in Fig. 1. The bremsstrahlung beam was collimated with lead. The diameter of the beam was 2 cm at the position of the target. At the first exposure a cobalt foil, 10 μ thick, was irradiated. The cobalt foil was produced by electrolysis on a tin sheet, whose surface was slightly copper-plated. The tin was then melted away, and a cobalt foil of uniform thickness was obtained. At the second exposure a copper foil, rolled out to a thickness of 10 μ, was irradiated.

The camera consisted of a cylindrical vessel of brass with a lid and a pump connection. A narrow tube was fitted at the front. At the top of this a thin entrance window of aluminium was mounted. Further, the camera had a holder in which the metal foils and the nuclear emulsions were mounted. The camera was surrounded by a thick lead shield. X-ray films were used for the adjustment of the camera along the synchrotron beam. The target was mounted in the holder at a narrow angle with the symmetrical axis of the camera; this was done to increase the irradiated quantity of matter. Four Ilford E.1 nuclear emulsions, 200 μ thick, 1″ × 2″, were placed in the holder in such a manner as to become parallel with the symmetrical axis in the camera. In addition,

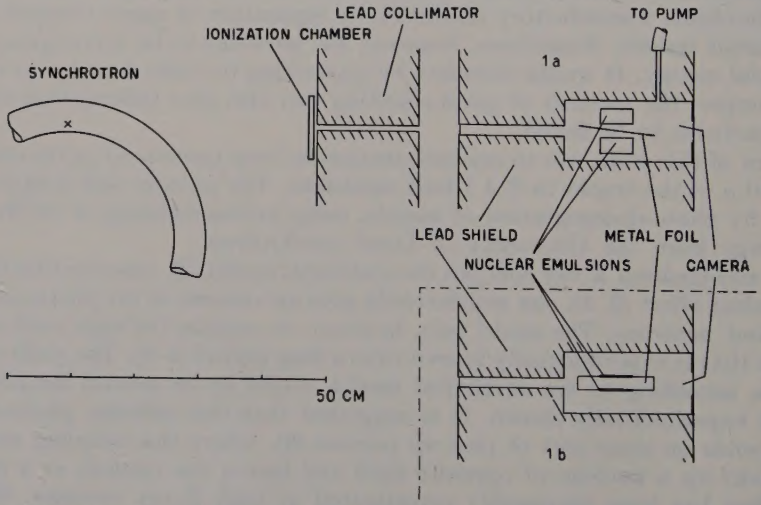

Fig. 1. Experimental arrangement of the photo-particle registration. The camera is shown horizontally in Fig. 1 a and vertically in Fig. 1 b, in order to present the arrangement of the target and the four emulsions.

these emulsions were placed at a distance from the centre of the camera sufficient to shield them from direct irradiation of the synchrotron beam. The emulsions were protected from the scattered radiation of the entrance window, as the latter had been moved forward a considerable distance.

The holder was placed in the adjusted camera. The camera was evacuated in order to decrease the stopping effect of the photo-particles in air before they were recorded in the emulsions. The camera was cooled with compressed air in order to keep the nuclear emulsions at a sufficiently low temperature during irradiation. A dose of approximately 500 roentgen was given at both exposures to the target. Only the relative dose was of interest; and this was measured by an ionization chamber placed in the beam. In the same manner a background exposure without target was made with the same dose.

Development

The method of development proved to be of the greatest importance for the resolution of the photo-particles into protons and deuterons. At first a diluted ID 19 developer and an amidol developer were used. Both, however, gave a poor grain density gradient in the neighbourhood of the end of the tracks. Finally a modified Van der Grinten developer (15) was used. As a buffer to the developer, 100 g Na_2CO_3 per litre was added to Van der Grinten's prescription. Thus, no pH variation in the emulsion was obtained, and consequently a more even development resulted. It was possible to find the grain density best adapted for grain-counting by varying the KBr percentage according to Stevens (16). Although the sensitivity of the E.1 emulsions varies somewhat from batch to batch, it was possible to attain about the same grain density in plates from different sendings. Normally 1 g KBr per litre was used.

An experiment was also made with a view to varying the grain density by fading. Exposed plates were placed at different humidities for some days. The plates were then developed in a normal way. In those plates where the grain density was changed, however, a notably uneven development was simultaneously obtained. The fading

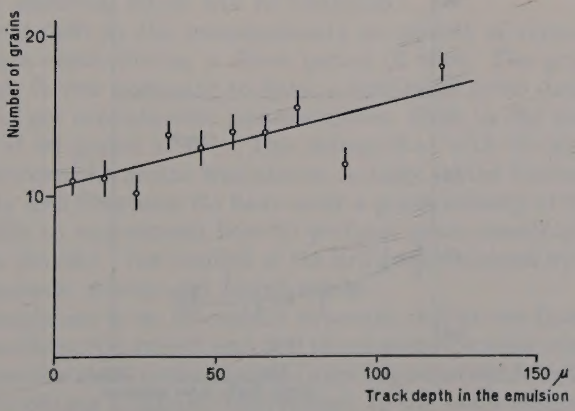

Fig. 2. The variation of the development with depth in a nuclear emulsion faded for 2 days in a relative humidity of 75 %. The last 10 μ of the tracks were grain-counted.

exerted the greatest effect on the surface layers (17). Fig. 2 shows the variation of the development in depth of an emulsion which for two days after exposure has been placed in a relative humidity of 75 % at room temperature.

The development was made according to the temperature cycle technique (18). A pressure method worked out in Lund (19) was used in order to get the emulsions speedily soaked in developer. The modified Van der Grinten developer was inactive at 5°C. The temperature of the warm stage was 20°C. By varying the time of the warm stage it was possible to vary the grain size to a certain extent. At 15 minutes, the grains had a mean diameter of 0.45 μ.

Measurements

A Zeiss binocular microscope was used with 95 × objective for the measurements. The horizontal projection of the track was measured with a Leitz ocular screw micrometer 12.5 ×. The depth of the end of the track in the emulsion was measured with the vertical fine focusing mechanism of the microscope; the latter was calibrated with gauge blocks. The thickness of the emulsion was determined before and after the development in order to determine the shrinkage factor. Values corresponding to the results of Rotblat and Tai (20) were obtained. The grain-counting was made at intervals of 12 μ in a horizontal direction. All tracks more than 40 μ in length that came from the target and entered the surface of the emulsion were measured, except those having a dip angle of more than 40°. The number of tracks going straight through the emulsion was noted.

The measured proton–deuteron tracks were compared with recoil proton tracks

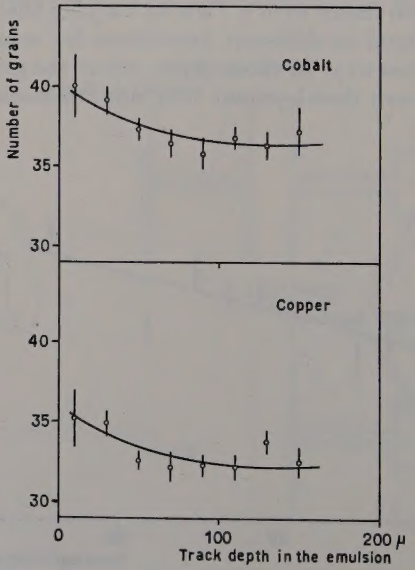

Fig. 3. The variation of the development with depth in the main plates. The last 40 μ of the tracks were grain-counted.

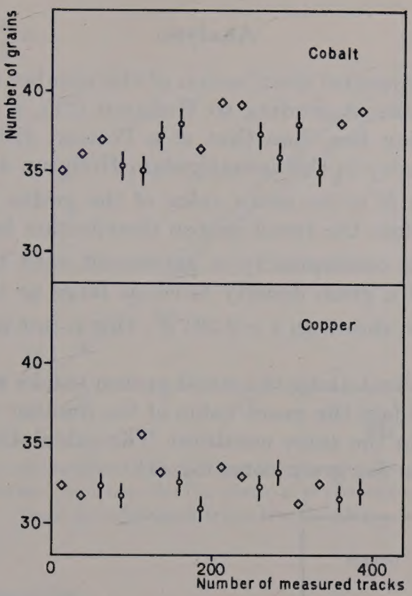

Fig. 4. Control of the convention. The number of grains in the last 40 μ of the tracks is plotted against the number of tracks. ○ marks recoil protons and ◇ marks photoparticles.

starting inside the emulsion. The recoil protons originate from neutrons entering the emulsion and hitting hydrogen nuclei in the gelatine. The development was investigated by means of these true proton tracks, which were uniformly distributed in the emulsion. A certain over-development in the upper part of the emulsion was observed and measured. This is shown in Fig. 3. All tracks were corrected for this effect. If this correction is not made, the short photo-particle tracks near the surface will have an excessive grain density. They will then be identified principally as deuterons; and an excessive deuteron effect will be obtained.

In order to avoid drift in the measurements on acount of subjective convention changes, these were made during a short period of time. The grain density must also be suppressed. It was necessary to have a maximum grain density of 40 grains in 40 μ in order to get reproducible measurements. Drift in the measurements was obtained already at 50 grains in 40 μ. This means that with the existing grain size, the gap length between the grains was almost as large as the diameter of the grains themselves. Byerly and Stephens (5) have used a grain density of 77 grains in 40 μ. But it is impossible to understand how to perform grain-counting reproducibly at such a high grain density. The control of the drift was obtained by measuring alternately proton–deuteron tracks and recoil tracks.

In one of the emulsions from the cobalt exposure and in one from the copper exposure, 200 proton–deuteron tracks and 200 recoil proton tracks were grain-counted. Immediately before the main measurements were begun, about fifty tracks were grain-counted in order to obtain a definite convention. In the main measurements no drift in the convention was observed. Fig. 4 shows the number of grains in the last 40 μ of the track plotted as a function of measured tracks.

Analysis

Fig. 5 shows the experimental distribution of the number of grains in the last 40 μ of the recoil proton tracks. According to Hodgson (21), a distribution is expected with a standard deviation less than that of a Poisson distribution with the same mean. For the grain density in this investigation Hodgson assigns a standard deviation, s, of $0.7\sqrt{N}$, where N is the mean value of the grains per section. In both the cobalt and the copper plate the recoil proton distribution had a standard deviation of $0.69\sqrt{N}$. This value is consequently in agreement with that of Hodgson. Byerly and Stephens have used a grain density twice as large as the one used here. Their recoil proton distribution shows an $s = 0.29\sqrt{N}$; this is not in agreement with Hodgson's value.

The grain density gradient along the recoil proton tracks was also measured. From this it is possible to calculate the mean value of the number of grains in the last 40 μ of the deuteron tracks in the same emulsion. The calculation is made by means of the well-known formulas for grain-counting (1).

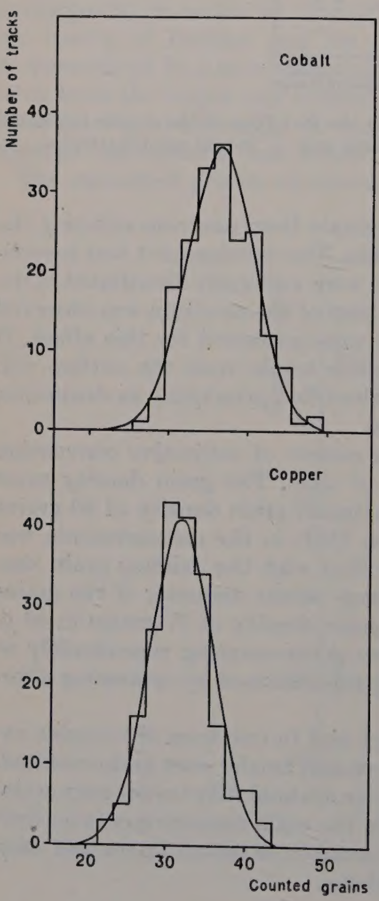

Fig. 5. The recoil proton distribution in the main plates with the fitted normal distribution. Grain-counting was made in the last 40 μ of the tracks.

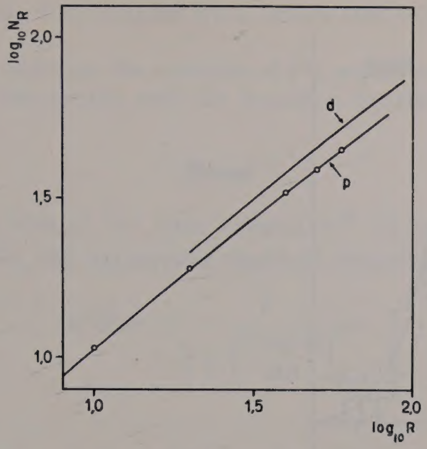

Fig. 6. Relationship between the residual range R in microns and the number of grains in residual range. p is the measured proton line from the Cu-plate. d is the calculated deuteron line. Similar lines are obtained from the Co-plate.

For singly charged particles

$$N_R = mF(R/m)$$

and hence

$$N^d_{40\,\mu} = 2N^p_{20\,\mu}\,.$$

R = residual range,
m = the mass of the particle,
N_R = the number of grains in residual range;
d and p mark the kind of particle.

The observed $N^p_{40\,\mu}$ is 36.5 for cobalt and 32.0 for copper. The calculated $N^d_{40\,\mu}$ is 42.8 for cobalt and 37.2 for copper.

Fig. 6 shows the grain density gradient along the recoil tracks.

It is assumed that the distribution of the number of grains in the last 40 μ of the recoil proton tracks is normal with the mean $N^p_{40\,\mu}$ and the standard deviation $s^p = 0.69\sqrt{N^p_{40\,\mu}}$. This hypothesis has been tested by comparing it with the observed distribution using the ordinary χ^2-measure. No indication of any deviation from the hypothesis was obtained. Fig. 5 also shows this normal distribution. The distribution of the number of grains in the same section of the photo-deuteron tracks is also assumed to be normal, with the mean $N^d_{40\,\mu}$ and a standard deviation $s^d = 0.69\sqrt{N^d_{40\,\mu}}$.

As, in this investigation, the grain density is low, and the modified Van der Grinten developer gives a $(N^d/N^p)_{40\,\mu}$ of about 1.17, it is impossible to expect a separation of single deuterons from protons by means of the grain-counting method. The photo-deuterons entering the plate will only produce a positive skewness of the photo-particle distribution. A distribution which is the sum of two normal distributions ought to be fitted to the observed distribution. The one corresponds to the proton distribution and is known from the recoil proton measurements. The other corresponds to the deuteron distribution and can be calculated as above. The areas of the two normal distributions are adjusted so that the sum of the distributions gives the best

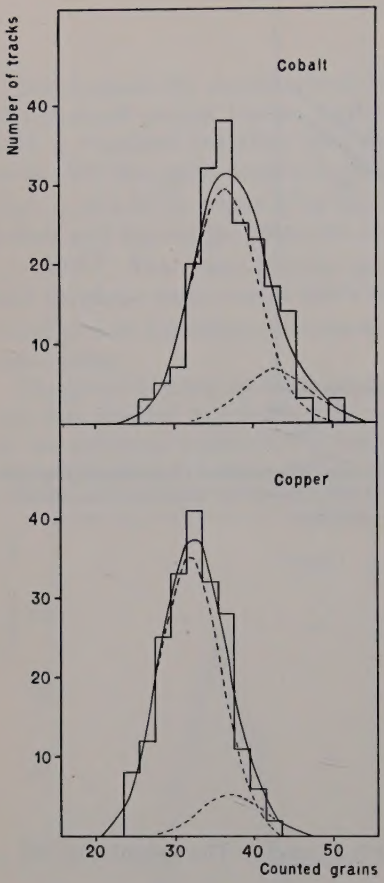

Fig. 7. The photo-particle distribution in the main plates with the two fitted normal distributions and their sum. Grain-counting was made in the last 40 μ of the tracks.

fit to the measured photo-particle distribution. This fit is made with the method of maximum likelihood (22). The likelihood function L is defined as

$$L = \pi_i \left[\theta p_i^p + (1-\theta)\, p_i^d\right]^{f_i}.$$

θ = the number of photo-proton tracks/the total number of photo-particle tracks.
p_i^p = the expected proportion of photo-protons falling in the interval i.
p_i^d = the expected proportion of photo-deuterons falling in the interval i.
f_i = the total frequency of photo-particles observed in the interval i.

In order to obtain the maximum likelihood estimate $\hat{\theta}$ of θ the likelihood equation is solved

$$\frac{\delta \log L}{\delta \theta} = \sum_i \frac{f_i}{\theta + \dfrac{p_i^d}{p_i^p - p_i^d}} = 0.$$

The obtained $\hat{\theta}$ of the two distributions is 0.81 for cobalt and 0.86 for copper. Fig. 7

shows the photo-particle distributions from cobalt and copper with fitted normal distributions.

It should be pointed out that the estimate of θ is sensitive to departures from the assumed normality of the proton and the deuteron distributions.

Error

In order to form an idea of the error arising in $\hat{\theta}$ on account of the relatively small size of the sample, the asymptotic standard deviation, $\varepsilon(\hat{\theta})$, is calculated.

$$\varepsilon^2(\hat{\theta}) = \frac{1}{n \sum_i p_i \left(\frac{d \log p_i}{d\theta}\right)^2_{\theta=\hat{\theta}}}$$

$p_i = \theta p_i^p + (1-\theta) p_i^d.$

n = the total number of photo-particle tracks.

The obtained $\varepsilon(\hat{\theta})$ of the two distributions is 0.053 for Co and 0.059 for Cu.

Results

The performed measurements of cobalt and copper gave the following value for the ratio between photo-deuterons and photo-protons

$$\text{Co: } Y(\gamma, d)/Y(\gamma, p) = 0.22 \pm 0.08,$$
$$\text{Cu: } Y(\gamma, d)/Y(\gamma, p) = 0.16 \pm 0.08.$$

The error stated above is the calculated asymptotic standard deviation. The background is 7.5 % and is shown in Fig. 8. From this it is obvious that only a small fraction of the background can be made up of deuterons. In the calculations, the

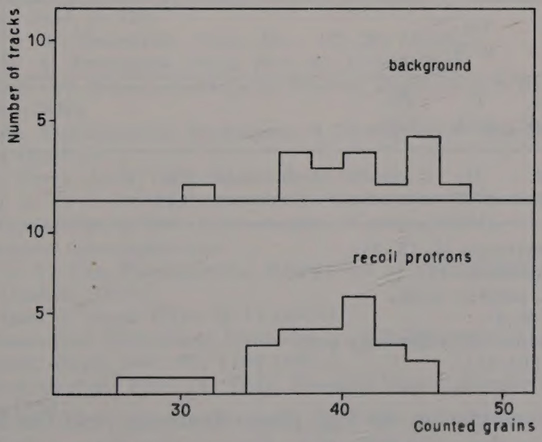

Fig. 8. The background referred to recoil protons. Grain-counting was made in the last 40 μ of the tracks.

background is neglected. The particles going straight through the emulsion have been assumed to be photo-protons on account of their high energy; they have been added to the measured photo-protons. Their number constitutes only a small percentage of the sample.

Discussion

Grain-counting in short tracks can give a certain amount of information. However, a separation of single deuteron tracks from proton tracks cannot be expected. The grain density ought not to exceed one grain per micron in order to obtain reprocucible values at the measurements. At the same time it is difficult to increase the grain density gradient so that $(N^d/N^p)_{40\,\mu} > 1.2$. Further, at a large gradient the difficulty arises of deciding whether the long tracks enter the surface or not. The limited grain density and the grain density gradient together with the given standard deviation $s \sim 0.7\sqrt{N}$ set limits to the resolution. In a large size of sample it is, however, possible, by means of statistical methods, to separate a proton–deuteron distribution into respective groups.

Table 1. The reported ratios of the photo-deuteron to the photo-proton yield $Y(\gamma,d)\,/\,Y(\gamma,p)$.

Max. X-ray energy MeV	$Y(\gamma, d)/Y(\gamma, p)$ of different elements	Method employed
24[a]	Co Cu In Ce Bi < 0.02 0.31 < 0.01 0.04 0.01	grain-counting
28[b]	S 0.02	activity measurement
30[c]	Co Cu 0.22 0.16	grain-counting
65[d]	S Cu 0.15 0.76	magnetic cloud chamber
300[e]	Be C Pb 0.16 0.13 0.20	two-crystal telescope at 90°
310[f]	Be C– a number of elements –Pb 0.21 0.12– a continuous increase –0.24	

[a] University of Pennsylvania (5, 13, 14).
[b] University of Saskatchewan (7).
[c] University of Lund, present work.
[d] Iowa State College (6, 8).
[e] Massachusetts Institute of Technology (12).
[f] Cornell University (10, 11).

In the present investigation the high photo-deuteron yield has been observed. Any marked difference in the yield from the adjacent elements—cobalt and copper—has not been observed. The yield obtained from copper is smaller than the value reported by Byerly and Stephens. Toms and Stephens (14) observed no photo-deuterons from cobalt. Ring (8) has reported the value 0.15 for the ratio $Y(\gamma, d) / Y(\gamma, p)$ from sulfur using bremsstrahlung of 65 MeV maximum energy.

Katz and Penfold (7) have measured the $(\gamma, d) + (\gamma, np)$ cross section curve from sulfur and were able to divide it into two parts. From this and from the integral cross section due to the (γ, p) reaction in sulfur (23) the value 0.02 is obtained for the ratio of the photo-deuteron to the photo-proton yield. Katz and Penfold used a bremsstrahlung of about 28 MeV maximum energy. Similar measurements have recently been reported for zinc and sulfur (24). The values reported in the present investigation are of the same order of magnitude as that of Ring. The values obtained with 300 MeV X-rays are also of this size. Thus it seems as if the photo-deuteron yield is remarkably constant over a large energy range.

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